

# The SWMF: Geospace Capabilities for Transition to Operations

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ATMOSPHERIC, OCEANIC  
AND SPACE SCIENCES

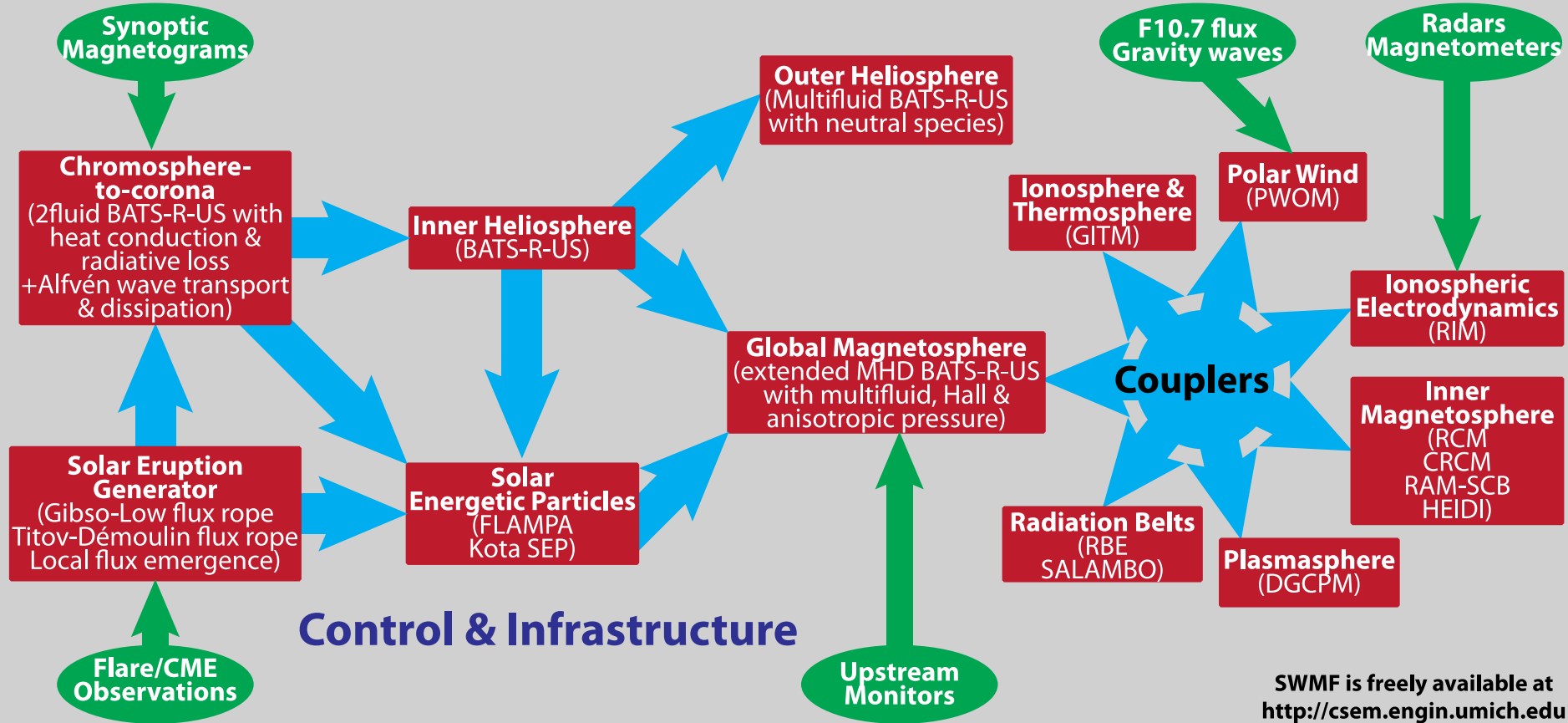
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# Model Coupling with SWMF

## Block Diagram of the Space Weather Modeling Framework



# X-MHD Model: BATS-R-US

## Time-stepping

Local explicit (CFL control) for steady state  
Global explicit  
Part steady explicit  
Explicit/implicit  
Point-implicit  
Semi-implicit  
Fully implicit

## Conservation laws

Hydrodynamics, MHD  
Ideal & non-ideal  
Hall  
Anisotropic pressure  
Semi-relativistic  
Multi-species  
Multi-fluid  
Ideal & non-ideal EOS

## Numerics

Conservative finite-volume discretization  
2nd (TVD), 4th (PPM) & 5th (MP)  
spatial order schemes  
Rusanov/HLLC/AW/Roe/HLLD  
Splitting the magnetic field into  $B_0 + B_1$   
Divergence B control  
CT, 8-wave, projection, parabolic-hyperbolic cleaning

**B**lock **A**daptive-**T**ree **S**olar-wind **R**oe-type **U**pwind **S**cheme

## AMR Library (BATL)

Self-similar blocks  
Cartesian grid  
Curvilinear grid (can be stretched)  
Supports 1, 2 and 3D block-adaptive grids  
Allows AMR in a subset of the dimensions

## Source terms

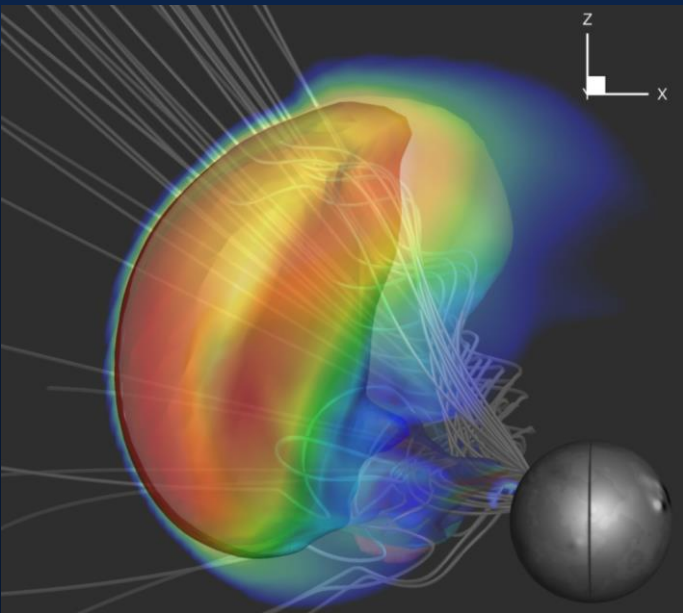
Gravity  
Heat conduction  
Ion-neutral friction  
Ionization  
Recombination  
Charge exchange  
Wave energy dissipation  
Radiative heating/cooling

## Auxiliary equations

Wave energy transport  
Radiation transfer (multigroup diffusion)  
Material interface (level set)  
Parallel ray-tracing  
Tabular equation of state

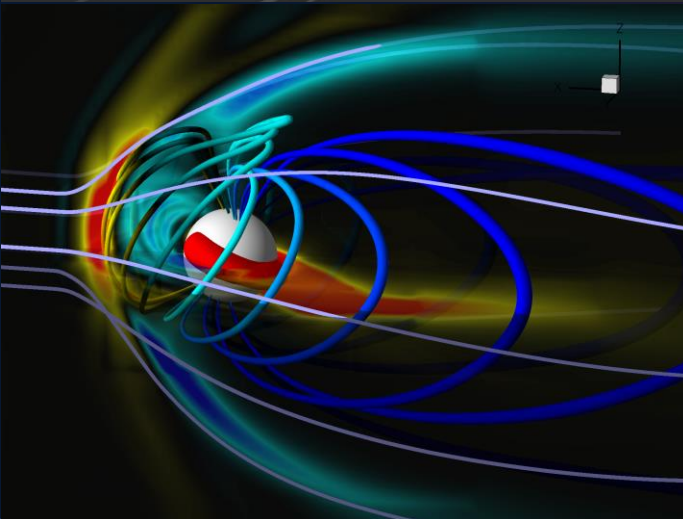


# Main Space Weather Applications



## ☀ **AWSM (Alfvén Wave Solar Model)**

- ☉ Chromosphere to 10 AU
- ☉ Turbulence-driven solar wind
- ☉ Input:
  - ☼ Synoptic solar magnetogram
  - ☼ Outward propagating turbulence Poynting vector at the inner boundary
- ☉ Free parameters (in simulation domain):
  - ☼ Perpendicular correlation length of turbulence
- ☉ Simulated observables:
  - ☼ SOHO, STEREO, SDO synthetic EUV, X-ray and visible images
  - ☼ Solar wind parameters anywhere between 1  $R_{\odot}$  and 10 AU

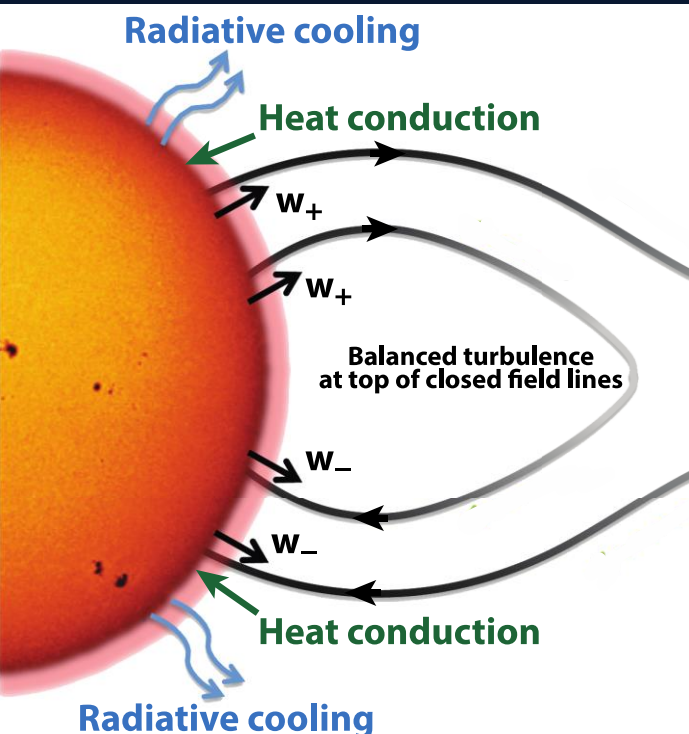


## ☀ **MARCIE (Magnetosphere with Ring Current and Ionospheric Electrodynamics)**

- ☉ BATS-R-US + RCM/CRCM + RIM
- ☉ Multifluid Hall MHD with anisotropic temperatures
- ☉ Input:
  - ☼ Upstream solar wind
  - ☼ Date/time (for magnetic axis)
  - ☼ F10.7 flux
- ☉ Simulated observables:
  - ☼ Dst, Kp, regional K, CPCP, ...
  - ☼ Plasma parameters anywhere in the magnetosphere



# AWS<sup>2</sup>M Model



## XMHD physics:

- Separate  $T_{\parallel}$ ,  $T_{\perp}$  and  $T_e$
- WKB equations for parallel and antiparallel propagating imbalanced turbulence ( $w_{\pm}$ )
- Non-WKB physics-based reflection of  $w_{\pm}$  results in turbulent cascade
- Correction for presumed uncorrelated waves  $w_{\pm}$  in the balanced turbulence near apex of closed field lines
- Physics-based apportioning of turbulence dissipation at the gyro-kinetic scales into coronal heating of various species
- Wave pressure gradient acceleration of solar wind plasma
- Collisional and collisionless electron heat conduction
- Radiative plasma cooling

## Boundary Conditions:

- Inner boundary is at the upper chromosphere where all temperatures are 50,000K
- Plasma density at inner boundary is  $2 \times 10^{17} \text{ m}^{-3}$  (to avoid chromospheric evaporation)
- Radial magnetic field is derived from synoptic solar magnetograms
- Poynting flux of outward propagating turbulence can be chosen within an observationally constrained range
- Perpendicular correlation length of turbulence can be chosen within an observationally constrained range

Sokolov et al., 2013  
Van der Holst et al., 2014



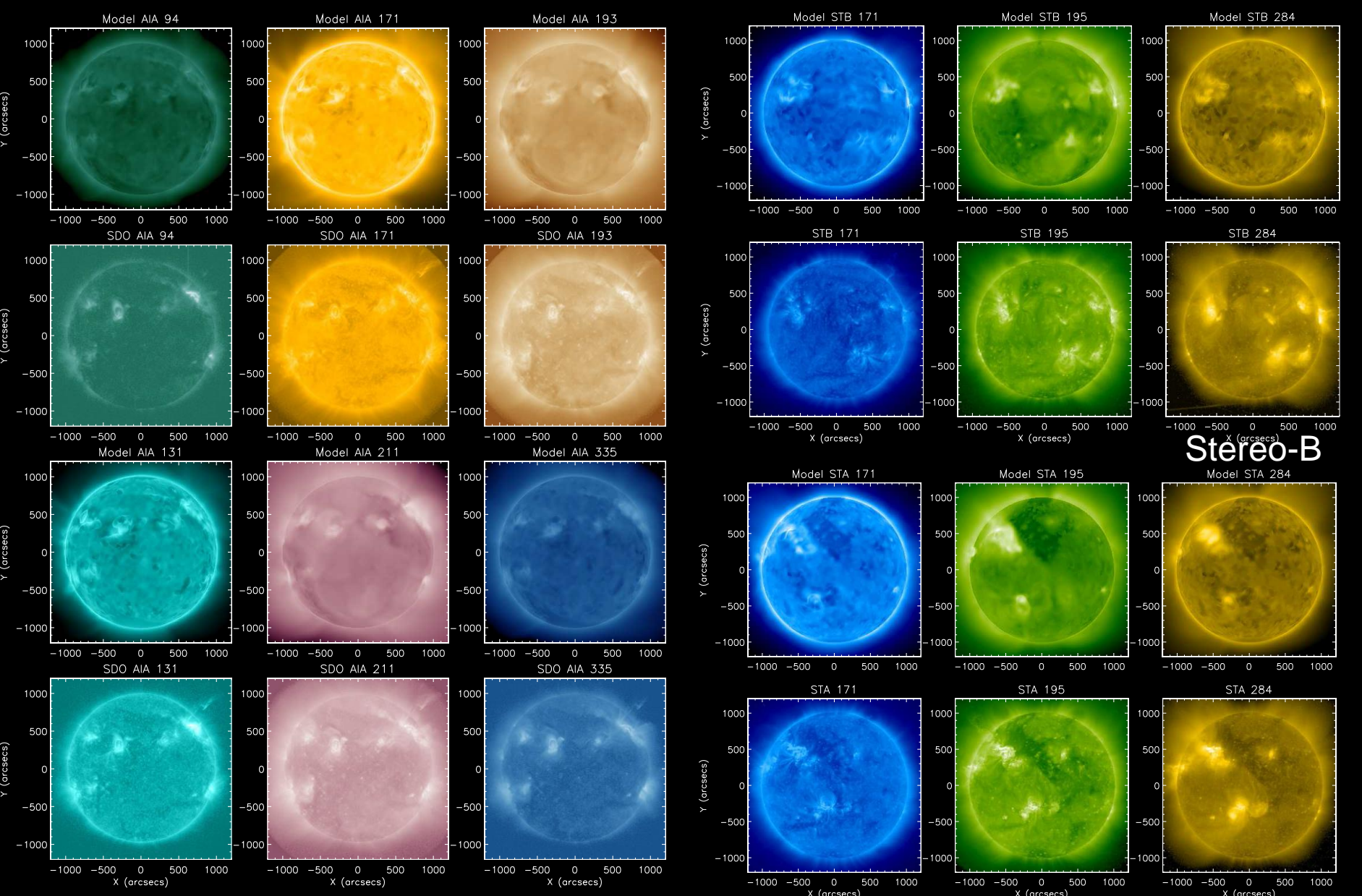
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# AWSM Comparison (March 7, 2011 20:00UT)



SDO

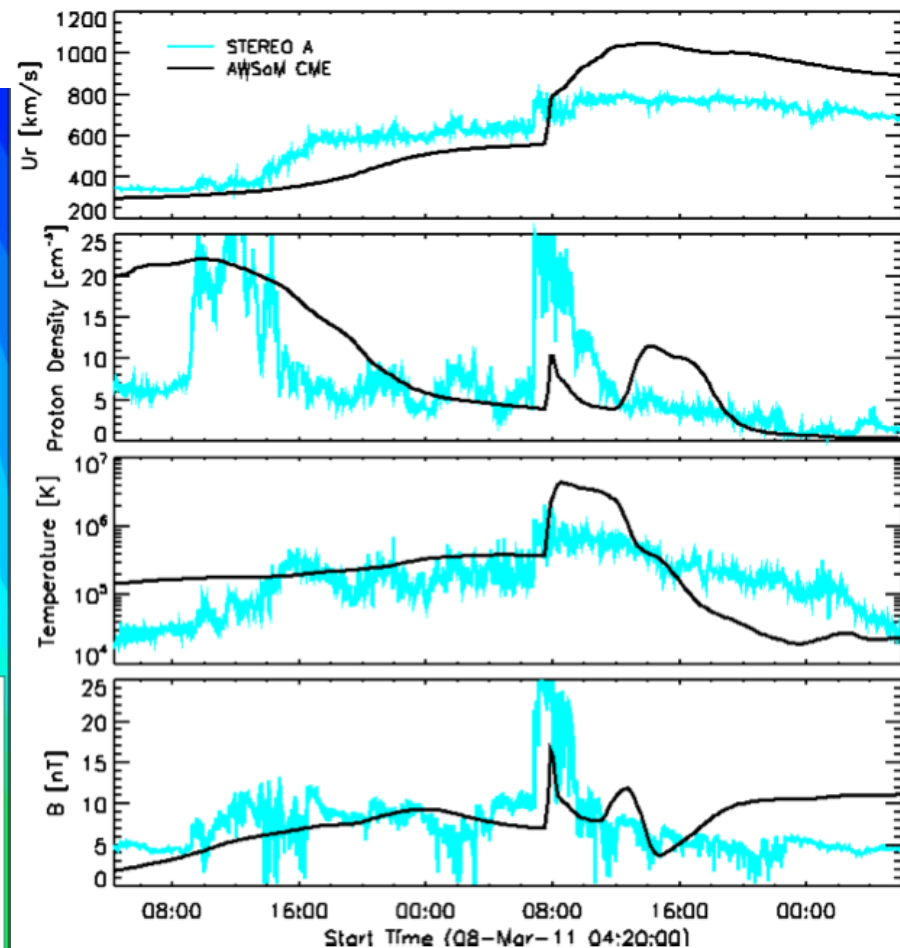
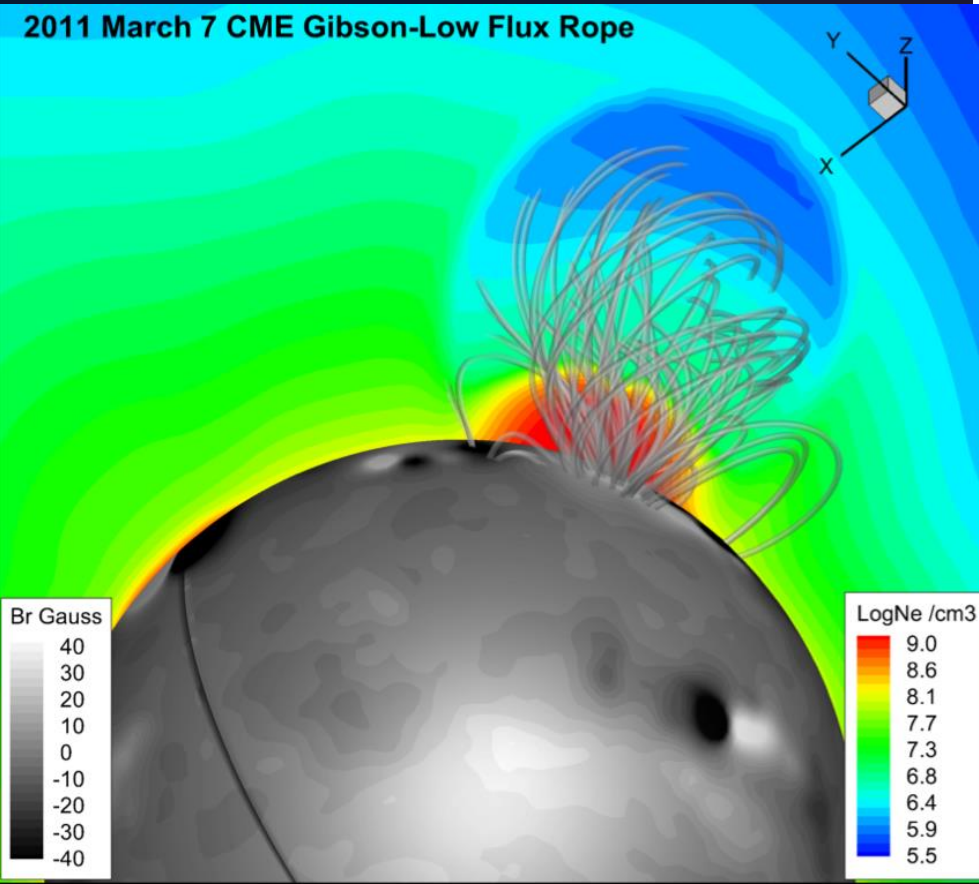
Stereo-A

# March 7th 2011 CME Simulation

## CME simulation with the AWSoM model:

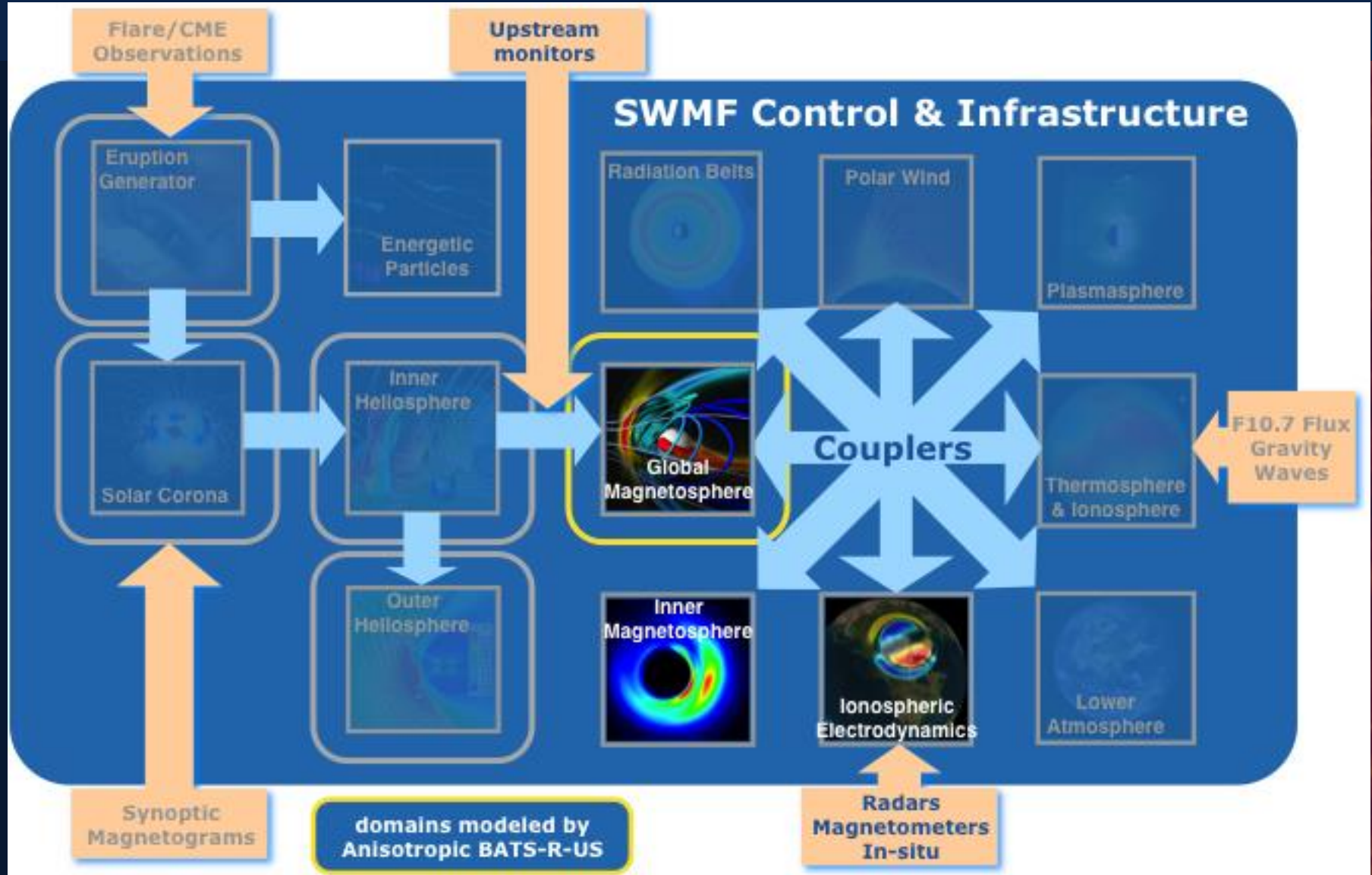
- Gibson-Low flux rope erupts from active region 11164
- The simulation matches the arrival time with 2 hours
- SIR-CME interaction crucial to CME structure at 1AU

M. Jin et al. in preparation



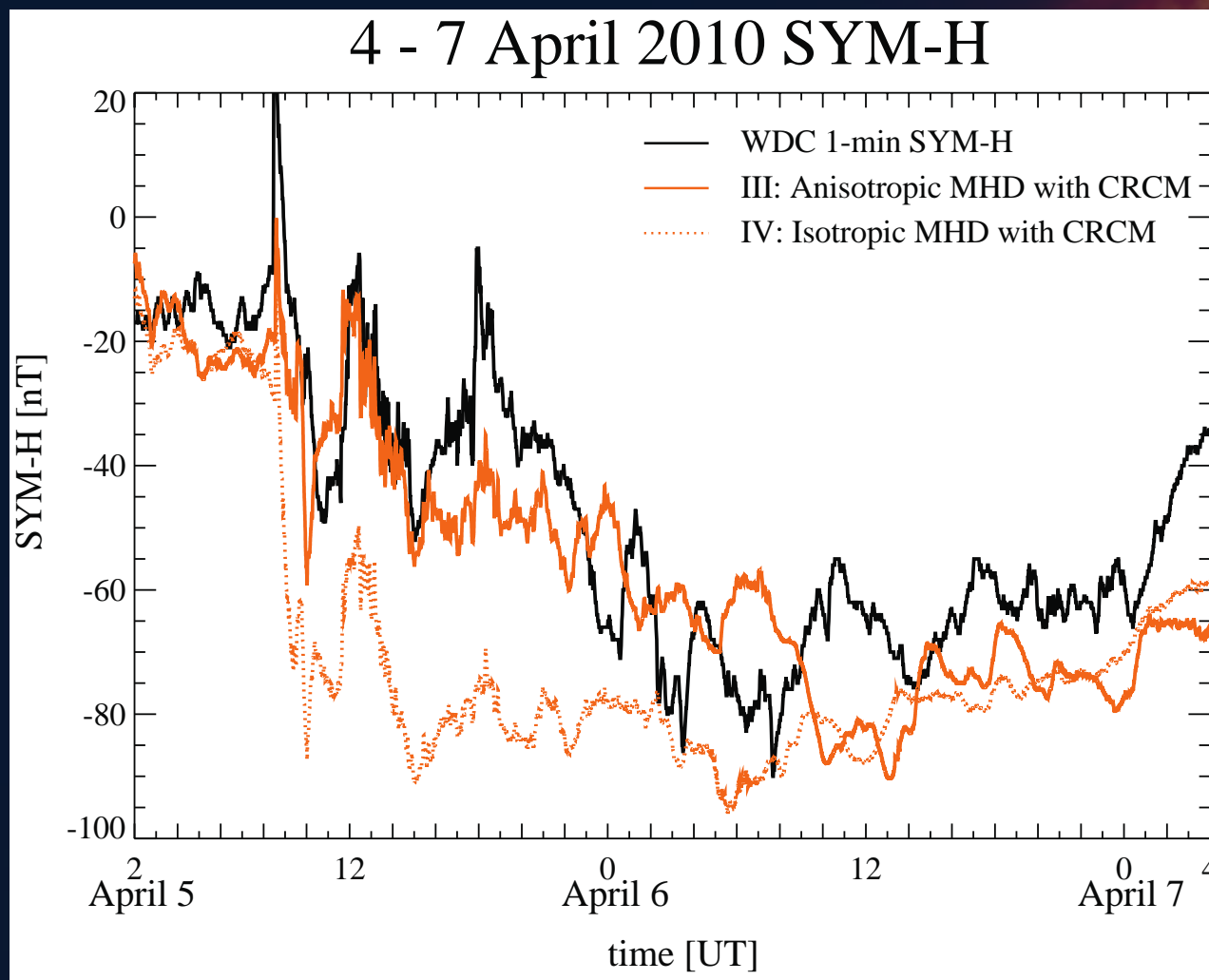


# MARCIE Model



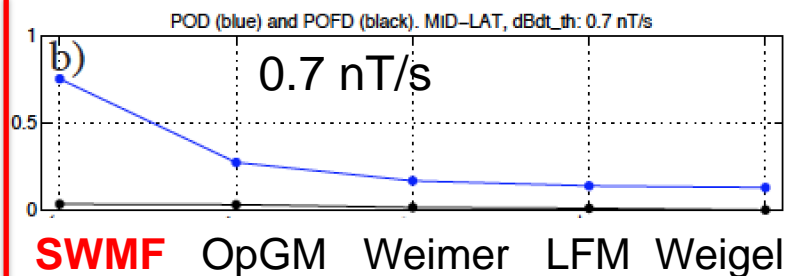
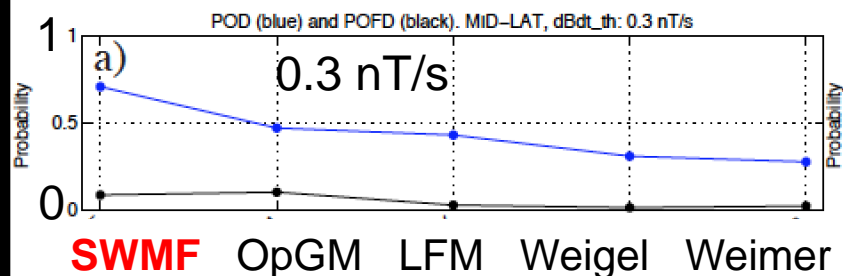


# MARCIE Comparison with the SYM-H Index (similar to Dst)

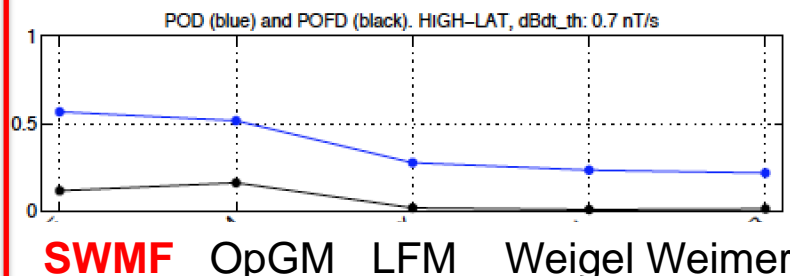
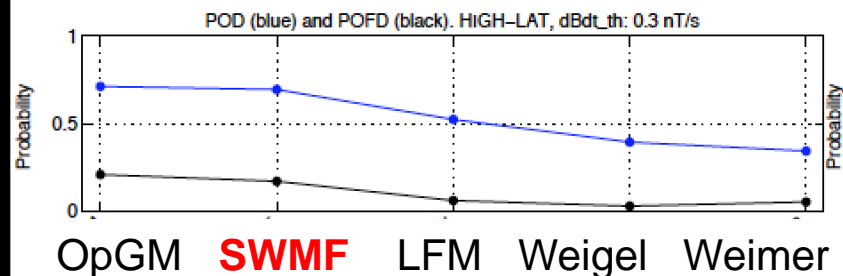


# CCMC Storm Validation: POD and POFD for the 4 threshold levels

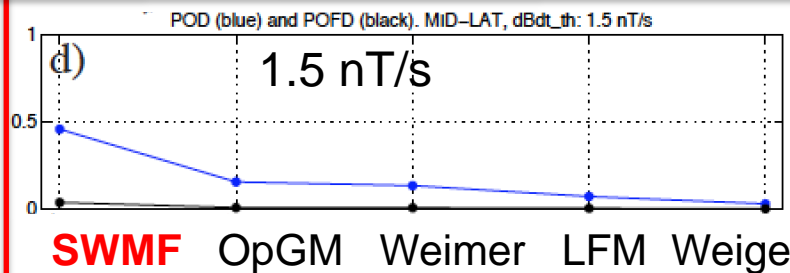
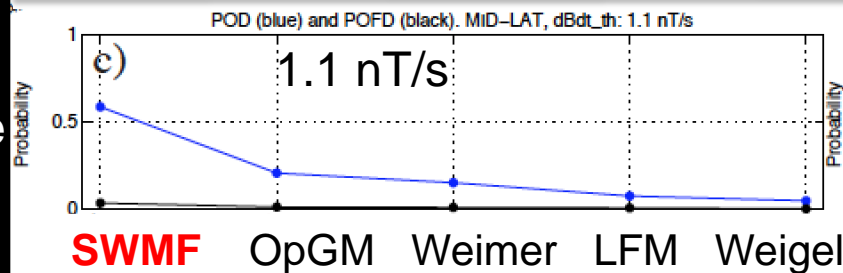
Mid  
Latitude  
stations



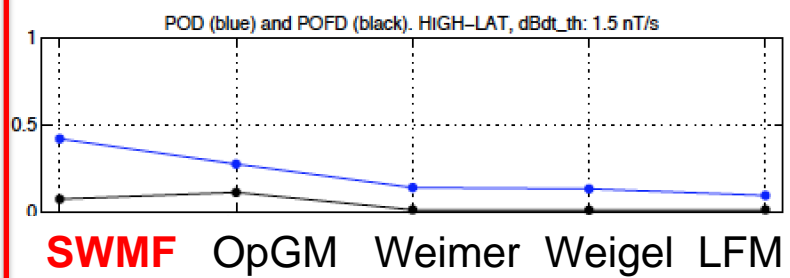
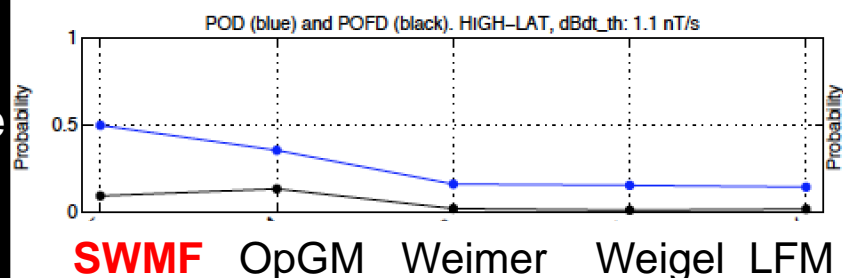
High  
Latitude  
stations



Mid  
Latitude  
stations



High  
Latitude  
stations



# CCMC K-index Validation (K threshold = 8)

Model	Heidke skill score	Critical Success Index	POD	POFD
<b>SWMF</b>	<b>0.44</b>	<b>0.33</b>	<b>0.39</b>	<b>0.03</b>
<b>SWMF,a</b>	<b>0.48</b>	<b>0.37</b>	<b>0.42</b>	<b>0.02</b>
OpenGGCM	0.32	0.25	0.34	0.06
LFM-MIX	0.07	0.04	0.04	0.00
WEIMER	0.16	0.11	0.11	0.01
WEIGEL	0.40	0.31	0.36	0.03

## High-latitude stations

- H (hits) – Number of cases where model and observation exceed threshold  
 F (false hits) – Number of cases where model exceeded threshold but observation did not  
 M (misses) – Number of cases where observation exceeded threshold but model did not  
 N (no hit) – Number of cases where neither model nor observation exceeded threshold

$$\left. \begin{aligned} \text{Heidke Skill Score} &= 2(H \cdot N - M \cdot F) / [(H+M) \cdot (M+N) + (H+F) \cdot (F+N)] \\ \text{Critical Success Index (Threat Score)} &= H / (H+M+F) \\ \text{Probability Of Detection (POD)} &= H / (H+M) \\ \text{Probability Of False Detection (POFD)} &= F / (F+N) \end{aligned} \right\} \begin{aligned} &(\text{perfect}=1, \text{no skill}=0) \\ &(\text{perfect}=0) \end{aligned}$$

Model	Heidke skill score	Critical Success Index	POD	POFD
<b>SWMF</b>	<b>0.71</b>	<b>0.60</b>	<b>0.74</b>	<b>0.03</b>
<b>SWMF,a</b>	<b>0.67</b>	<b>0.54</b>	<b>0.62</b>	<b>0.02</b>
OpenGGCM	0.26	0.19	0.24	0.04
LFM-MIX	0.28	0.18	0.20	0.01
WEIMER	0.46	0.33	0.34	0.00
WEIGEL	0.33	0.22	0.23	0.00

## Mid-latitude stations





# Research Codes vs. Operational Codes

Research Code	Community Code	Operational Code
Run and analyzed by a small group of scientists	Run by highly trained scientists at CCMC, analyzed by community members	Run and analyzed by non-scientists
Often “hacked” together with no software discipline	Streamlined version of research code	Highly controlled software product
No manual, few comments	Occasional manual, some comments	Extensive manual and detailed comments
No version tracking, bug fix history	Version tracking, some bug fix history	Version tracking, detailed bug fix history
Validation by developer	Independent validation	Continuous validation, skill score evolution
Code changes as the developer wishes	Occasional code updates	Highly controlled regular code update process
No intellectual property concern	CCMC “rules of the road” apply, but no contractual agreement	Intellectual property is major concern, lawyers involved
Developers guard source code as a trade secret	Source code is available only to CCMC staff	SWPC treats code as government property
Only limited information is published about algorithmic and model details	CCMC staff does not modify code	All algorithmic and model details must be clearly stated



# Transition Process

## ☀ Step 1: Transition to community use (CCMC)

### ☉ CCMC

- ☞ provides access to space research models
- ☞ tests and evaluates models
- ☞ runs a real-time space weather model testbed
- ☞ supports space science education

### ☉ CCMC does not

- ☞ hardens codes
- ☞ writes code documentation
- ☞ optimizes model parameters
- ☞ fixes code bugs (features?)

### ☉ Code developers

- ☞ train CCMC staff on model use
- ☞ modify research codes to minimize the number of “knobs”
- ☞ fix code bugs (features?)

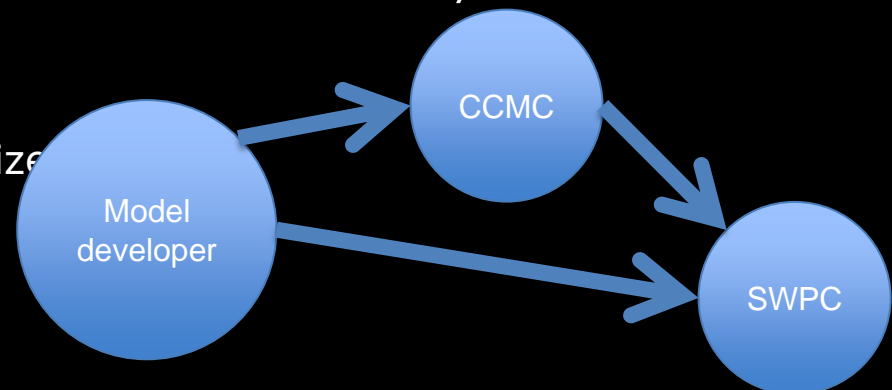
## ☀ Step 2: Transition to operations (SWPC)

### ☉ Code developers

- ☞ periodic code updates
- ☞ standby software support
- ☞ code documentation
- ☞ optimize default options

### ☉ SWPC

- ☞ code hardening (nuclear war resistant)
- ☞ code documentation
- ☞ licensing agreements
- ☞ software traceability and conventions
- ☞ transition to new platforms
- ☞ periodic skill evaluation and updates
- ☞ + many other issues



# What is the Developer Cost of Transition?

## ☀️ Estimate for SWMF

- ☉ Transition/support to CCMC: ~0.5 FTE/year
  - ☞ Simplify options
  - ☞ Fine-tune defaults
  - ☞ Train personnel
  - ☞ Regular consultations
  - ☞ Regular updates
- ☉ Transition/support to SWPC: ~ 1 FTE/year
  - ☞ Manual
  - ☞ Robustness
  - ☞ Software engineering
  - ☞ Intellectual property issues
  - ☞ Support services
  - ☞ Regular updates

☀️ 1.5 FTE/year is probably a robust estimate for most large codes





# Summary

- ☀ With 20 faculty and 15 Ph.D. students **CSEM** is a major participant in space weather research
- ☀ Over the last 20 years we developed the **high-performance BATS-R-US multiphysics X-MHD code** and the SWMF framework
- ☀ Major application areas are solar-heliosphere (**AWS<sup>®</sup>M**) and magnetosphere (**MARCIE**)
- ☀ Our next challenge is fluid-kinetic coupling (**PIC/hybrid** and **DSMC**)
- ☀ **AWS<sup>®</sup>M** and **MARCIE** are running at **CCMC** and are available in Runs-for-Request simulations
- ☀ **SWMF** and its components are downloadable (after registration) from <http://csem.engin.umich.edu>

